

Feasibility study on optical vortex generation at Shanghai deep ultraviolet free-electron laser*

DENG Hai-Xiao (邓海啸)^{1,†}

¹Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
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Coherent light with orbital angular momentum (OAM) is of great interest. Recently, OAM light generation by coupling a relativistic electron beam with a Gaussian mode laser pulse at the high harmonics of a helical undulator has been demonstrated experimentally. In this paper, the possibility of delivering coherent OAM light at the 3rd harmonic of the Gaussian mode seed laser is discussed for the Shanghai deep ultraviolet free-electron laser (SDUV-FEL). Considerations are given on the experiment setup, the expected performance and the possible measurement method.

Keywords: Free-electron laser (FEL), Orbital angular momentum (OAM), Shanghai deep ultraviolet (SDUV), Cross-correlation

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I. INTRODUCTION

As is well known, light carries both linear and angular momentum. One particular application of the linear momentum of light is optical tweezers [1], in which a highly focused laser beam is utilized to provide an attractive or repulsive force, typically pico-Newton, depending on the refractive index mismatch to physically hold and move microscopic dielectric particles. Meanwhile, the orbital angular momentum (OAM) of light can also be transferred to particles, causing them to spin, and thus provide the conceptual leap in both understanding and application. In fact, after the breakthrough production of laser beams carrying defined amounts of OAM in the laboratory [2], many branches of optical physics, including nonlinear and quantum optics, information encoding and, of course, optical manipulation has been significantly impacted [3]. Undoubtedly, continuing advances in optical and other technologies will continue to drive forwards the science of OAM light and its applications.

In the last two decades, particle accelerator-based light sources, e.g., free-electron lasers (FELs) have been developed worldwide to satisfy the dramatically growing demands of high brightness and short-wavelength radiation, especially x-ray pulses which enable simultaneous probing of both the ultra-small and the ultra-fast worlds. The successful user operations of FEL facilities [4–8] in x-ray regimes have announced the birth of x-ray laser. Considering its flexible and reliable properties, OAM of light becomes a new topic for the FEL community [9–11], besides ultra-short pulse [12–15], full coherence [16–21] and fast polarization switch [22–25]. More recently, using electron beam as a mode-converter on the test accelerator for SLAC's next linear collider, a Gaussian laser has been experimentally converted to an OAM mode in an 800 nm FEL [26]. This paves the way for the coherent OAM x-ray pulse with unprecedented brightness.

The Shanghai deep ultraviolet FEL (SDUV-FEL) is a mis-

cellaneous accelerator test facility for x-ray FEL principles and technologies [27], such as echo-enabled harmonic generation lasing [28], two-stage cascaded high-gain harmonic generation [29] and crossed-planar undulators [30], etc. It is found that SDUV-FEL is well suited for the lasing experiment of coherent OAM light with some minor modifications. In this paper, the possibility of delivering coherent OAM light at the 3rd harmonic of the 1047 nm Gaussian mode seed laser is explored for the SDUV-FEL, a plan for the experiment is described and the expected performance is outlined.

II. SETUP FOR OAM GENERATION AND EXPECTED PERFORMANCE AT SDUV-FEL

In contrast to a normal seeded FEL scheme, the OAM light generation relies on a harmonic interaction between the electron beam and a Gaussian seed pulse in a circularly polarized undulator to naturally produce a helical energy modulation in the electron distribution, as shown in Fig. 1. After passing through the dispersive chicane, the energy modulation is then converted into the helical micro-bunching, and thus the screw-distribution electrons emit and amplify coherent OAM light in a downstream planar undulator.

The helical modulator here is supposed to be a five-period Apple-II type undulator, which is now served as the high power terahertz emitter with the femtosecond electron bunch [31], as shown in Fig. 2(a). The magnetic structure consists of four standard Halbach magnet rows above and below the electron orbit plane, and it can be operated in linear, elliptical or circular polarized modes. The upper-front and lower-back magnet arrays can be moved independently along the longitudinal direction within a range of 60 mm. The resonant wavelength of the Apple-II modulator can be calculated by the undulator equation $\lambda_1 = \lambda_u(1 + K^2)/2\gamma^2$ for circular polarization, where γ is the electron energy normalized to the rest energy mc^2 , λ_u is the undulator period, and $K = eB_0\lambda_u/2\pi mc^2$ is the undulator parameter, with B_0 being the peak magnetic field of the undulator. At $B_0 = 0.15$ T and $\lambda_u = 0.1$ m, Fig. 2(b) illustrates the orbit of a 135 MeV electron, with the resonant wavelength of the helical modulator being 2094 nm in this case.

In such experimental configurations of the seeded FEL, an

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† Corresponding author, denghaixiao@sinap.ac.cn

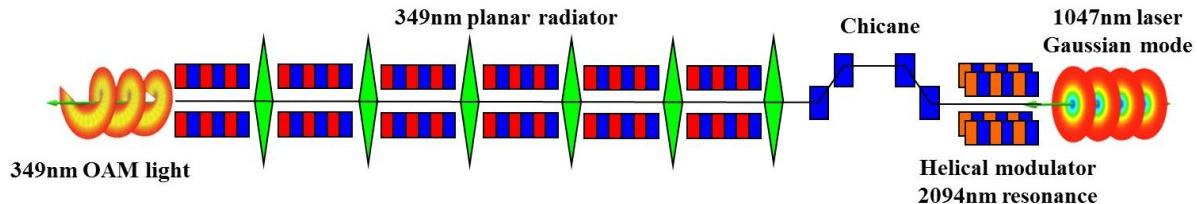
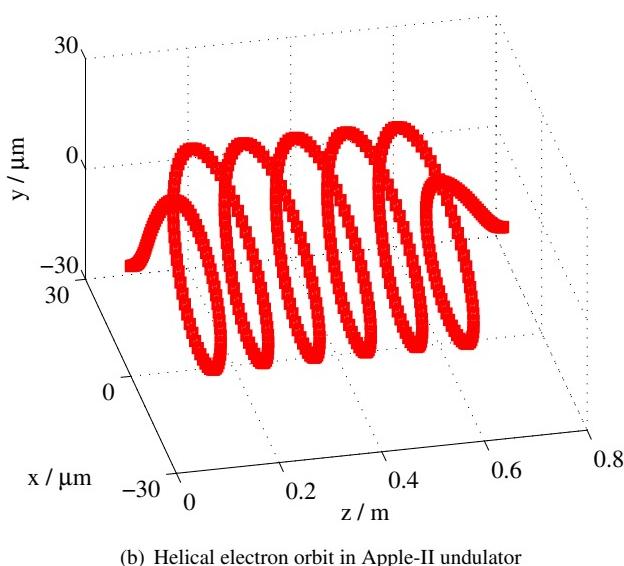


Fig. 1. (Color online) Schematic setup for OAM light generation at SDUV-FEL.



(a) Apple-II undulator



(b) Helical electron orbit in Apple-II undulator

Fig. 2. (Color online) The Apple-II undulator and the helical orbit of 135 MeV electron beam.

initial uniform electron beam interacts with the 1047 nm Gaussian mode laser pulse in the helical modulator. As a consequence of three-dimensional harmonic interaction, the field profile $E(r)/E_0 = \exp(-r^2/w^2)$ of the linearly polarized seed laser excites a helical modulation via the second harmonic resonance. The coupling is proportional to the radial variation of the Gaussian laser field, thus the electrons on-axis are un-

modulated, while those at the helical position $ks - h\varphi = n\pi$ and the radial position $r = w/\sqrt{2}$ receive the largest energy kick, given by

$$\Delta\gamma_{\max} \cong \frac{eK^2N\lambda_u^2E_0}{10\pi\lambda^2mc^2\omega}, \quad (1)$$

where, N is the modulator periods number, s is the electron longitudinal position, e is the charge of an electron, k is the wave number of the seed laser, and h and φ are the azimuthal mode and angle, respectively. The following dispersive magnetic chicane, characterized by the matrix transport element R_{56} , converts the energy modulation into a helical bunching. At the chicane exit, the bunching factor corresponding to the n^{th} harmonic of the seed laser and the h^{th} azimuthal mode, is then expressed as

$$b(n, h) = |\langle e^{-inkz - ih\varphi} \rangle|. \quad (2)$$

In order to ensure that the OAM light dominates in the subsequent radiator, the correlated helical structure must exceed the intrinsic shot noise of the electron beam. Thus, a three-dimensional universal algorithm [32] is used for numerically optimizing the laser-beam interactions in the helical modulator. In the simulation, both the seed laser (1047 nm, 2 MW) and the electron beam (2 μm rad emittance, 100 A peak current, 5 keV sliced energy spread) are focused to 250 μm.

Figure 3(a) shows the bunching factor dependences on the chicane dispersion R_{56} , when a field strength of $E_0 = 56$ MV/m at the laser waist in the modulator yields an energy modulation amplitude of 25 keV. For the 3rd harmonic of the seed laser, $h = -3$ OAM light shows the maximum bunching factor of about 12% while other azimuthal modes are well controlled. In the case of the optimal dispersion $R_{56} = 1.2$ mm, Fig. 3(b) illustrates the beam distribution after density modulation, and a left-handed helical density modulation is clearly observed. We note that there exists a strong bunching factor at lower harmonics of the seed laser, e.g., $n = 1$, $h = -1$ and $n = 2$, $h = -2$, but this is not under consideration here, because the radiator is chosen to be resonant at the 3rd harmonic.

With the optimized parameter above, the helically micro-bunched beam is imported to GENESIS [33] for the OAM light lasing calculation and the main radiator is tuned to the 3rd harmonic of the seed laser, i.e., 349 nm. The main radiator consists of six segments of 1.5 m planar undulator with undulator period of 25 mm and undulator parameter of 1.42. The 12% coherent bunching factor of the $h = -3$ OAM mode is significantly larger than the intrinsic shot noise in modern FELs, and

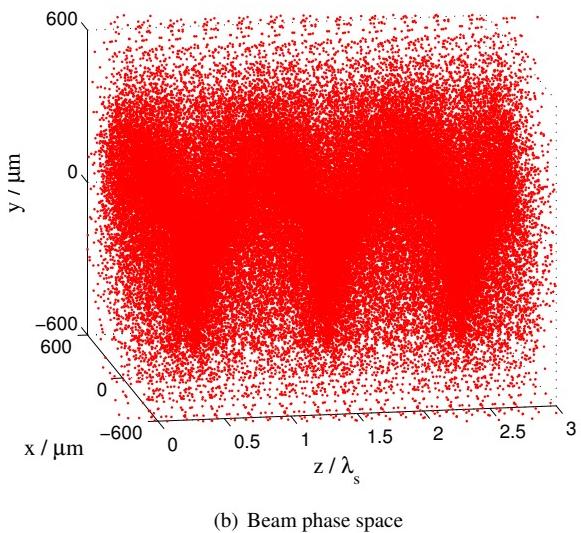
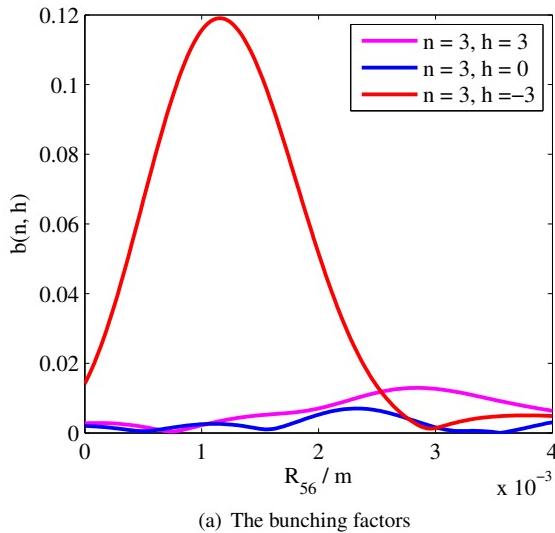


Fig. 3. (Color online) The bunching factor and the optimized beam distribution after the dispersive chicane.

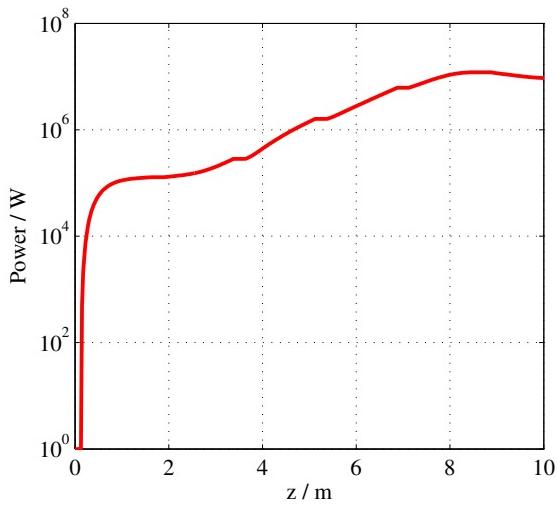


Fig. 4. (Color online) The 349 nm radiation power growth in the main radiator undulator.

it is expected that the $h = -3$ OAM mode will be dominant at the entrance of the radiator, and will be amplified further. The simulated 349 nm radiation evolution is given in Fig. 4, where the radiation peak power exceeds 10 MW and saturates after 5 segments of the radiator.

Now we consider the azimuthal mode of the 349 nm radiation in the radiator. Fig. 5(a) illustrates the distribution of radiation intensity and phase after the first ten periods of radiator. It is clear from the radiation phase that the large bunching factor of $h = -3$ is responsible for the initial production of the coherent OAM light with $h = -3$. The imperfect roundness in the simulated intensity patterns indicates that other optical modes also exist in the 349 nm radiation, which is mainly due to the asymmetries of the electron beam, and the impurity OAM mode excitation in the helical modulator [26].

Figures 5(b) and 5(c) plot the azimuthal performances of the 349 nm radiation after the first segment of the radiator and after saturation, respectively. With a greater length of the radiator undulator, the $h = -3$ OAM mode will be surpassed by the $h = 0$ Gaussian mode, which is due to the shorter gain length of the Gaussian mode than that of the OAM mode. This arises an important issue for the OAM mode lasing of an FEL source, besides the initial helical density modulation, i.e., the gain length of the interested OAM mode should be short enough to ensure that it dominates in the radiator undulator with respect to other optical modes.

III. OAM LIGHT MEASUREMENT METHOD

In Ref. [26], the OAM radiation was confirmed experimentally from the diffraction pattern when passing through a slit and an iterative phase reconstruction procedure from the known transverse profiles of radiation, which may be utilized in the experiment of SDUV-FEL.

Here, we propose and investigate an alternative way to the cross-correlation method widely used for characterizing FEL properties [34] — it shall be more straightforward to observe cross-correlations of the OAM radiation field in the transverse plane. The cross-correlation intensity are defined as

$$\zeta(x, y) = |E(x, y) + E(x, -y)|^2. \quad (3)$$

Therefore, one of the arms should be the mirror image of the FEL radiation in cross-correlation. Using the simulated radiation mentioned above, we have Fig. 6 to illustrate a set of cross-correlation intensities for three positions of the radiator, i.e. $z = 0.25$ m, 1.5 m and 6 m, respectively. One sees obvious difference in the transverse pattern between the Gaussian mode and OAM light. In addition, the six petals in a 2π angular period confirms the fact of an OAM FEL radiation with an absolute topological charge of $h = 3$.

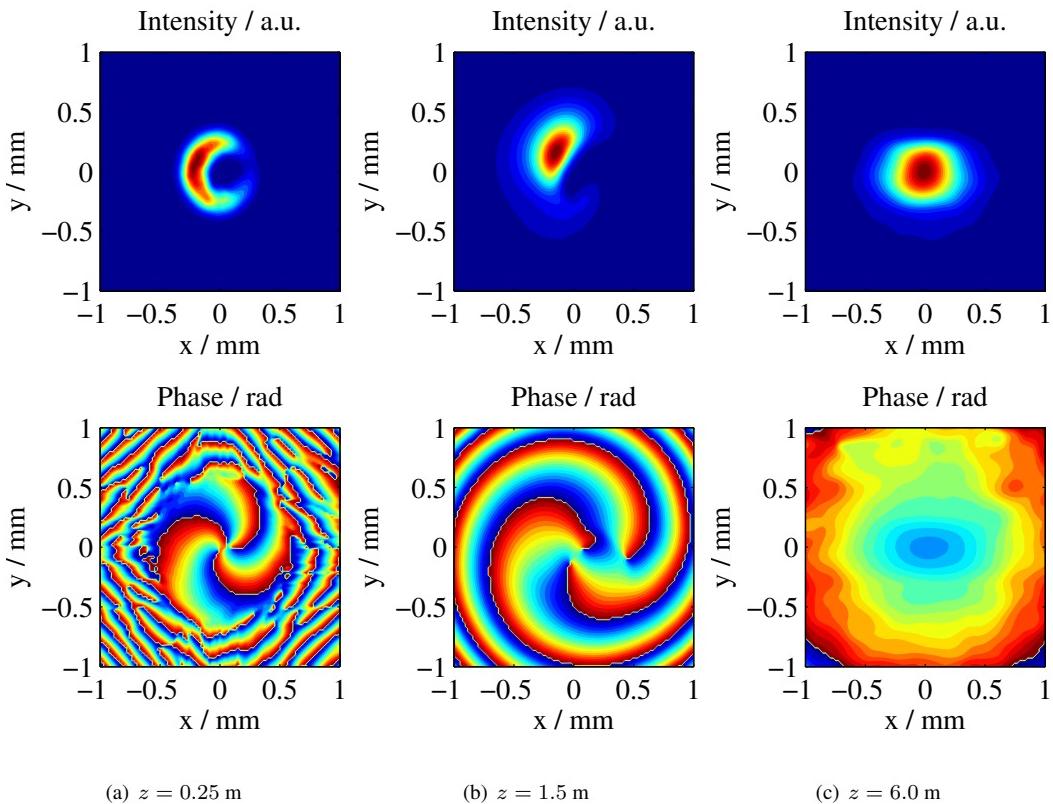


Fig. 5. (Color online) The azimuthal distribution of 349 nm radiation in the radiator undulator. (a) at the position of $z = 0.25$ m, (b) at the position of $z = 1.5$ m and (c) at the position of $z = 6.0$ m.

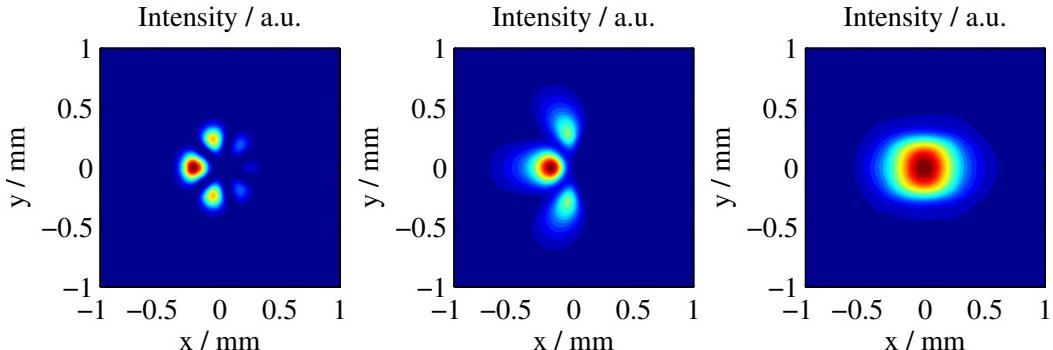


Fig. 6. (Color online) The expected cross-correlation of 349 nm OAM radiation at the SDUV-FEL undulator position of 0.25 m, 1.5 m and 6.0 m, respectively.

IV. SUMMARY

In summary, coherent OAM light generation from a relativistic electron beam has been recently demonstrated in the accelerator lab, by transforming the electron beam distribution to a helix by a Gaussian mode laser. In this paper, together with a 3rd harmonic up-conversion, one possible situation of an OAM lasing experiment on SDUV-FEL is presented. The preliminary considerations on the experiment setup and ex-

pected performance are discussed. Moreover, we propose a cross-correlation method for OAM light characterization. It is shown that the $h = -3$ OAM light at the 3rd harmonic of the 1047 nm Gaussian laser can be effectively generated. It is worth stressing that the calculation here is not fully optimized and there is still room for improvement, e.g., the helical modulation and the electron beam size in the radiator can be further matched, and the linac beam dynamics can be optimized for the interested OAM light, rather than a Gaussian

mode. We expect that OAM light approach can be extended to the short-wavelength FELs, with the most recent seeding schemes [11, 20, 21] and helical undulator driven harmonic lasing scheme of an FEL oscillator [35].

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